EVALUATION OF GREENHOUSE GAS EMISSIONS FROM AEROBIC AND ANAEROBIC WASTEWATER TREATMENT PLANTS IN SOUTHEAST OF ITALY

Ezio Ranieri*°, Gianfranco D'Onghia*, Luigi Lopopolo*, Petros Gikas**, Francesca Ranieri, Eleni Gika**, Vincenzo Spagnolo****, Ada Cristina Ranieri****°°.***

**Università degli Studi di Bari, Dipartimento di Biologia, Bari, Italy*

*** Technical University of Crete, School of Chemical and Environmental Engineering, Chania, Greece*

****Università degli Studi di Foggia, Dipartimento di Dipartimento di Economia, Management e Territorio, Foggia, Italy*

*****Politecnico di Bari, Dipartimento Interateneo di Fisica, Bari, Italy*

°°Università Internazionale Telematica Uninettuno, Roma, Italy

° Author to whom correspondence should be addressed: ezio.ranieri@uniba.it.

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Abstract

An evaluation of the operative functioning data of 183 Wastewater Treatment Plants (WWTPs) in Apulia (Southeast of Italy) has been carried out aimed to assess their Green House Gases (GHGs) emissions and the level for which the use of anaerobic sludge treatment should be more convenient in terms of electricity consumption and of GHGs emissions. Out of the 183 studies WWTPs, 140 are practicing aerobic digestion of sludge, while the remaining 43 are practicing anaerobic digestion of sludge. WWTPs in Apulia are serving about 4,81 million PE (Population Equivalent), yielding approximately 600,000-ton equivalent CO_2 per annum. The production of GHGs emissions has been estimated by evaluating the contribution of CO_2 deriving from: a) electric energy consumption (fossil CO_2), b) biogenic CO_2, c) N_2O and d) CH_4 emissions. The present study investigates a number of technical measures for upgrading the existing WWTPs, so to reduce GHGs emissions through the amelioration of CH_4 production and capture in the anaerobic step, and through reducing the production of biogenic N_2O and CO_2 emissions in the aerated basin. The methodology employees artificial intelligence-based control for upgrading the aerobic oxidation of the organic carbon and the nitrification-denitrification steps. As a result, GHGs emissions are expected to be reduced by approximately: 71% for CH_4, 57% for N_2O, 20% for biogenic CO_2 and 15% for fossil derived CO_2.

1 Introduction

Wastewater treatment is a global source of greenhouse gases (GHGs), particularly, carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (Ahn *et al*., 2010; Daelman *et al*., 2012; Schneider *et al*., 2014). As a result, wastewater treatment is a significant contributor to the overall GHG emissions in European Union (EU) and is reported as such under the UN Framework Convention on Climate Change (UNFCCC). Therefore, Wastewater Treatment Plants (WWTPs) operation, have a significant share to climate change and air pollution (Shahabadi *et al.*, 2009; Larsen *et al.*, 2015; Sweetapple *et al.*, 2014).

According to the European Green Deal (EC, 2019), the EU has embraced ambitious goals for the reduction of greenhouse gas emissions (EC, 2021) along with pollution reduction and circular economy objectives (Parravicini *et al.*, 2022).

During the biological wastewater treatment processes are produced carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), while CO_2 is also emitted for the production of the energy required for the WWTP operation. To the extent that electric energy production is based on fossil fuels, CO_2 correlated to the electric energy consumption may be directly reduced by enhancing the energy efficiency of the WWTPs. In this way both the reduction of environmental impacts and the decrease of treatment cost (due to energy savings) can be accomplished simultaneously (Ranieri *et al.*, 2003; Ranieri and Swietlik, 2010; Ranieri *et al.*, 2012; Siatou *et al.*, 2016; Al Bataina *et al.*, 2016; Gorgoglione *et. al* 2016; Acquafredda *et al.*, 2018; Herrera *et al*, 2020; Petrella *et al.*, 2021; Ranieri *et al.*, 2021;).

CO_2, CH_4 and N_2O have increased due to anthropogenic activities such as production and use of fossil fuels and other agricultural and industrial activities (Cakir and Stenstrom, 2005, Delre *et al.*, 2019); while CH_4 produced from sewage treatment has been found to constitute about 5% of the global methane sources (El-Fadel and Massoud, 2001). To compare the effect between different gases, their global warming potentials (GWP) in the wastewater treatment plant emissions were estimated and referenced to CO_2 equivalent (CO_2eq).

According to the estimations of the United Nation Framework Convention on Climate Change (UNFCCC), in 2018 N_2O and CH_4 emissions from wastewater treatment and discharge in industrialized countries (Annex I) contributed 2.6% and 3.6% to the total CO_2eq emissions, respectively (UNFCCC, 2018). At the same time, the possibility to make wastewater management energy-neutral (or even energy-positive) has attracted considerable attention (Gikas *et al.,* 2017; PowerStep, 2018a; Menduni *et al.*, 2020; Sgobba *et al.*, 2022), and some actors have pleaded to completely offset GHG emissions from wastewater, with a view to achieving climate neutrality also with reference to similar waste and wastewater treatment (Van Lienden *et al.,* 2010; Ragazzi *et al.*, 2014; Ciudin *et al.,* 2014; Capodaglio *et al.*, 2016; Petrella *et al.*, 2016a and 2016b; EUDP, 2017; Gikas and Ranieri*,* 2014; Kalimeris *et al.*, 2017; Moustakas *et al.,* 2020; Spagnolo *et al.*, 2020; D'Onghia *et al.*, 2021; Gikas *et al.,* 2022; Cosanti *et al.* 2022). Aerobic and Anaerobic based sludge digestion treatments have a significant impact to GHGs emissions (Cakir and Stenstrom, 2005), it is thus important to analyse their functioning and possibility of treatment processes upgrade.

According to the US Environmental Protection Agency EPA (2013), 3% of all US electricity consumption is related to wastewater treatment. The total electric energy consumption for the operation of WWTPs in Germany has been estimated as 4,200 GWh/year (Enerwater 2015), while in Italy it has been estimated as 3,250 GWh/year (Campanelli *et al.* 2013; Foladori *et al.* 2015). The latter corresponds to about 0.5 billion Euros per year. It is thus obvious that there is a need to reduce the energy requirements for WWTPs operation. However, in reality an average increase by 12% to the energy requirements for WWTPs operation between 2013 to 2018 has been observed in many Italian WWTPs, which corresponds to increase of about 182 GWh/year. The latter is due to WWTPs upgrades employing energy intensive processes, because of the increasingly stringent environmental standards (Acquedotto Pugliese, 2019, 2020, 2021).

In a previous work (Ranieri *et al*., 2021) a comparison between Italian anaerobic and aerobic sludge management WWTPs operating by two of the largest Water Companies in Italy (AQP and HERA) was carried out. The study investigated the energy consumption and cost associated with the management of the two types of WWTPs.

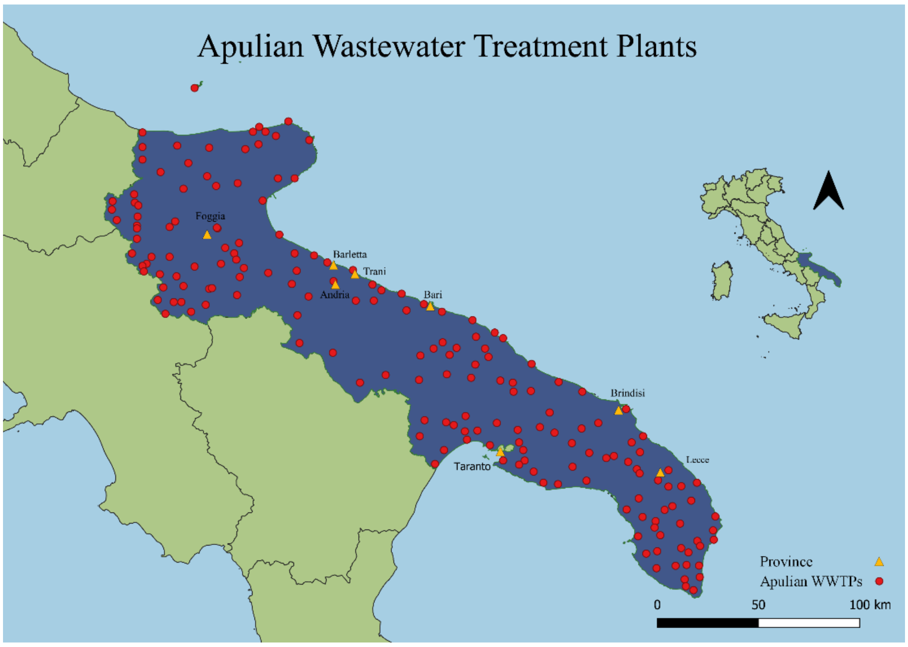


Figure 1 – Apulian WWTPs

The present study aims to investigate the electric energy consumption and of the GHGs emissions of the 183 Apulian (Italy) WWTPs, practicing either anaerobic or aerobic sludge managed, by one of the biggest Italian Water Management Companies –Acquedotto Pugliese S.p.a. (AQP). The locations of the studied WWTPs are marked on the map of Apulia (Figure 1). Specific objectives of this study are:

- To analyse the electrical consumption in aerobic and anaerobic sludge management WWTPs, assessing the level of which the use of anaerobic sludge treatment should be more convenient.
- To estimate the GHGs production from domestic WWTPs.
- To assess adequate measures to mitigate GHGs emissions quantifying their decrease.

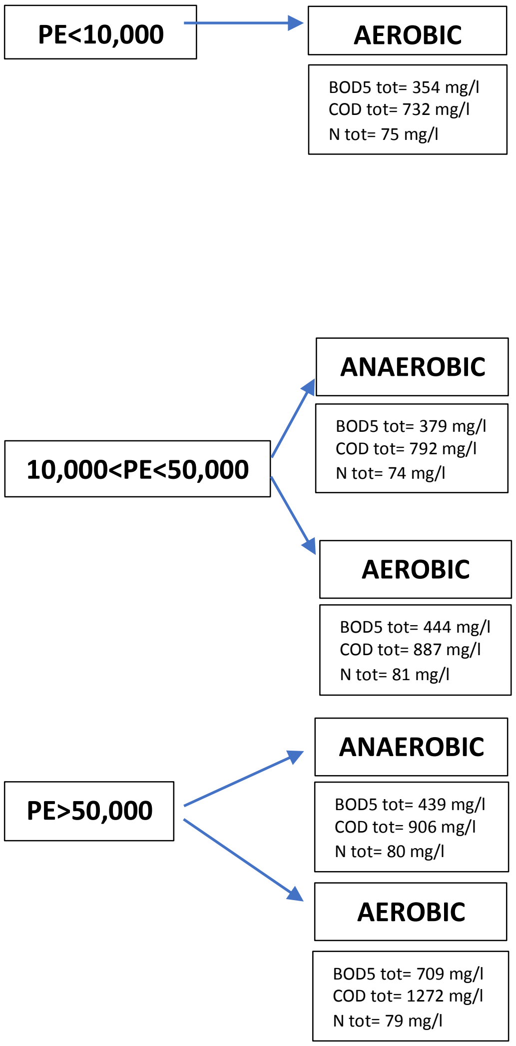
2 Materials and methods

Acquedotto Pugliese S.p.a. (AQP) manages 183 WWTPs in the entire region of Apulia, out of which 140 are equipped with aerobic digestion sludge facilities, while the remaining 43 are equipped with anaerobic digestion sludge facilities.

Table 1 reports all the Apulian WWTPs divided by size (< 10,000 PE (90 WWTPs); 10,000 PE < Size < 50,000 PE (73 WWTPs); > 50,000 PE (20 WWTPs)) and the relative average qualitative characteristics of inlet wastewater (BOD_5, COD and total nitrogen).

Table 1. Classification of the Apulian WWTPs with respect to their size and type of sludge treatment (anaerobic or aerobic), and major average inlet wastewater characteristics

Apulian WWTP Municipal (Potentiality in PE).



Triggianello (595); Poggiorsini (658); Sammichele di bari (8,569); Montegrosso (107); Spinazzola (7,252); Cisternino (8,767); San Donaci (5,449); Torchiarolo (4,497); Villa Castelli (8,577); Accadia (685); Alberona (694); Anzano Di Puglia (1,875); Ascoli Satriano (a) (2,523); Ascoli Satriano (b) (2,546); Bovino (1,792); Cagnano Varano (4,451); Cairano (324); Candela (2,822); Carapelle (6,565); Carlantino (1,100); Carpino (4,550); Casalnuovo Monterotaro (1,107); Casalvecchio Di Puglia (1,816); Castelluccio Dei Sauri (1,583); Castelluccio Valmaggiore (1,005); Castelnuovo della Daunia (1,426); Celenza Val Fortore (1,557); Celle San Vito (116); Borgo Libertà (21); Chieuti (2,112); Lido di Chieuti (368); Deliceto (2,613); Faeto (643); Villaggio S, Leonardo (164); Borgo Incoronata (657); Guardia dei Lombardi (760); Ischitella (3,188); Isole Tremiti (970); Lesina (9,327); Lido del Sole (4,535); Borgo Mezzanone (865); Mattinata (5,758); Monte Sant'Angelo (a) (6,203); Monte Sant'Angelo (b) (4,903); Monteleone Di Puglia (1,426); Motta Montecorvino (665); Ordona (1,994); Orsara di puglia (1,637); Panni (964); Peschici (5,300); Pietra Montecorvino (2,722); Rignano Garganico (1,163) Rocchetta Sant'Antonio (1,243); Rodi Garganico (7,551); Roseto Valfortore (1,185); San Marco La Catola (613); San Paolo Civitate (6,654); Santagata Di Puglia (1,637); Serracapriola (3,432); Stornara (7,271); Stornarella (6,734); Troia (7,046); Vico Garganico (6,832); Volturino (1,179); Zapponeta (2,859); Aradeo (6,436); Carmiano-Magliano (8,168); Castro (9,890); Collepasso (4,117); Corsano (9,423); Montesano Salentino (3,921); Morciano (8,120); Neviano (4,756); Novoli (9,466); Poggiardo (8,882); Presicce (4,836); S, Cesarea Terme (3,450); Specchia (4,655); Sternatia (2,936); Supersano (5,831); Taurisano (6,845); Castellaneta Marina (3,916); Faggiano (3,391); Marina di Ginosa (6,313); Maruggio (5,741); Montemesola (5,859); Palagianello (8,700) Lido di Chiatona (598); Torricella (4,449); Avetrana (1,590).

Acquaviva (20.926); Cassano Murge (11.378); Gioia Del Colle (33.207); Mola Di Bari (25.318); Putignano (40.275); Ruvo Di Puglia (47.049); Santeramo In Colle (19.673); San Ferdinando Di Puglia (20.871); Carovigno (33.175); Fasano (34.127); Francavilla Fontana (26.397); Mesagne (16.798); Ostuni (27.737); San Pietro Vernotico (20.789); Torre Santa Susanna (15.119); Copertino (17.404); Gallipoli (42.036); Nardò (25.940); Campi salentina (17.426); San Cesario Di Lecce (33.031); Monteiasi (31.247); Laterza (15.802); Massafra .(48.729); Taranto (b) (43.490).

Acquaviva (20,926); Alberobello (17,787); Casamassima (19,290); Castellana Grotte (23,943); Conversano (39,307); Giovinazzo (36,623); Locorotondo (14,559); Noci (15,666); Polignano a mare (18,229); Turi (15,795); Canosa (48,907); Margherita Di Savoia (17,612); Minervino (12,845); Trinitapoli (18,763); Ceglie Messapica (20,495); Latiano (11,875); Oria (15,570); San Pancrazio Salentino (10,378); Apricena (10,688); Lucera (19,128); Lucera (12,509); Ortanova (18,388); San Giovanni Rotondo (33,755);San Marco In Lamis (16,912); Sannicandro Garganico (13,593); Vieste (21,792); Carpignano Salentino (12,741); Casarano (33,055); Castrignano Del Capo (13,759); Cavallino (22,351); Galatina (41,184); Galatone (26,160); Melendugno (25,823); Otranto (10,706); Squinzano (32,348); Taviano (13,970); Tricase (19,325); Ugento (13,042); Uggiano La Chiesa (12,242); Vernole (12,238); Castellaneta (18,700); Crispiano (17,478); Ginosa (18,771); Lizzano (19,982); Manduria (18,285); Martina franca (34,026); Mottola (16,849); Palagiano (11,804); Pulsano (13,202); Carosino (30,734).

Altamura (98,333); Bari est (600,770); Bari ovest (345,945); Bitonto (87,559); Corato (69,654); Gravina in Puglia (54,509); Molfetta (56,614); Monopoli (72,619); Andria (217,513); Barletta (135,653); Bisceglie (76,136); Trani (66,497); Brindisi (103,389); Cerignola (74,120); Foggia (175,446); Manfredonia (68,782); San Severo (95,345); Lecce (134,769); Maglie (70,698); Taranto (a) (203,381).

Bitonto (87,559).

The approach taken in the present analysis also considers the electric energy consumption of two different treatment configurations, which use aerobic or anaerobic processes for sludge management. The effluent characteristics for all WWTPs comply with the treatment effluent standards (BOD_5: 25 mg/L, TSS: 35 mg/L). Most secondary treatment plants consist of aerobic biological treatment based on the activated sludge process with solids retention time (SRT) of about 10 days, and aerobic or anaerobic digestion for biosolids treatment. In some cases, a primary clarifier has been installed upstream of the aeration tank. The major influent average characteristics of the studied WWTPs are summarized in Table 2.

Table 2 – Apulian WWTPs influent average characteristics, total flow and electrical energy consumption

Number of WWTPs	PE (total)	Q (total) m_3/d	Energy (total) Kwh/d	BOD_5 average mg/L	COD average mg/L	N average mg/L	Specific electric energy Kwh/m^3
183	**4,807,354**	**676,932**	**497,858**	**426**	**874**	**79**	**0.735**

The GHGs emissions have been distinguished between direct emissions derived from the process (CO_2 biogenic, N_2O, CH_4) and indirect emissions (CO_2 from fossil fuels), as well as between emissions from operation and from infrastructure. In the categories "direct emissions", we inventoried all sources addressed by the IPCC guidelines (IPCC *et al*., 2006; IPCC *et al*., 2019), considering the CO_2 biogenic, N_2O and CH_4. The same applies to the emission categories listed in the "Specifications with guidance at the organization level for quantifying and reporting greenhouse gas emissions and removals" (ISO 14064-1, 2019), as far as applicable.

A wide survey has been summarized in Table 3, reporting the GHG emission factors for N_2O, CH_4 and biogenic CO_2 with the relevant recent literature.

Table 3-– Overview of the N_2O, CH_4 and biogenic CO_2 factors

WWTPs	**N_2O EMISSION FACTOR**	**REFERENCES**
12 WWTPs, United States	0.01%-1.8% N_2O/Nin	Ahn *et al.* 2010
12 WWTPs , Italy (PE < 15.000)	3.4×10^{-3} kgN_2O/kgTNrem	Marinelli *et al.* 2021
(PE > 15.000)	6.6×10^{-4} kgN_2O/kgTNrem	Marinelli *et al.* 2021
2 WWTPs, China (Orbal oxidation ditch)	3.6×10^{-3} kg N_2O/kg TNrem	Yan *et al.* 2014
(Reversed A^2O)	2.3×10^{-3} kg N_2O/kg TNrem	Yan *et al.* 2014
(Anoxic/anaerobic/Oxic)	0.8×10^{-3} kg N_2O/kg TNrem	Yan *et al.* 2014
7 WWTPs, Australia (BNR)	0.006–0.253 kgN_2O–N kg$N^{-1}_{denitrified}$	Foley *et al.* 2010
Estimated value	0.01 kgN_2O–N kg$N^{-1}_{denitrified}$	IPCC, 1997
Estimated value	0.005 kgN_2O–N kg$N^{-1}_{denitrified}$	IPCC, 2006
Estimated value	0.016 kg N_2O-N/kg N	IPCC, 2019
1 Pilot WWTP, Switzerland	0.12 and 0.356% of influent TN	Lotito *et al.* 2012
1 WWTP, United States (11,000 PE)	3.5×10^{-4}kgN_2O– Nkg$N^{-1}_{influent}$	Czepiel *et al.* 1995
1 WWTP, United Kingdom (210.000 PE)	0.036% of influent TN	Aboobakar *et al.* 2013
1 WWTP, Germany (60.000 PE)	0.001% N_2O/NLoad	Sumer *et al. 1995*
1 WWTP, Germany (60.000 PE)	0.02% N_2O/NLoad	Sommer *et al.* 1998
1WWTP, Japan	0.01%-0.08% N_2O/NLoad	Kimochi et al. 1998
2WWTPs, Germany	0.001 % N_2O/ NLoad	Tumendelger *et al.* 2019
1WWTP, Japan	0.03–0.14 % N_2O/ NLoad	Tumendelger *et al.* 2014
1 WWTP, Denmark (265.000 PE)	0.15–4.27 % N_2O/ NLoad	Yoshida *et al.* 2014
WWTPs	**CH_4 EMISSION FACTOR**	**REFERENCES**
1 WWTP, United States (11,000 PE)	0.34 % kg CH_4kg influentCOD^{-1}	Czepiel *et al.* 1993
2 WWTPs, Germany	0.01 KgCH_4/kgCODin	Tumendelger *et al.* 2019
1 WWTP, Poland (17,200 PE)	0.6% kgCh$_4$/kgCOD$_{load}$	Karolinczak 2021
4 WWTPs, China (Anoxic/anaerobic/Oxic)	0.58 KgCO_2/KgCODrem	Bao *et al.* 2014
(Anoxic/oxic process)	0.68 KgCO_2/KgCODrem	Bao *et al.* 2014
(Oxidation ditch)	0.76 KgCO_2/KgCODrem	Bao *et al.* 2014
(Sequencing batch react.)	0.07 KgCO_2/KgCODrem	Bao *et al.* 2014
12 WWTPs, Italy (PE < 15.000)	1.7×10^{-3} kgCH_4/kgCODin	Marinelli et al. 2021
(PE > 15.000)	2.7×10^{-4} kgCH_4/kgCODin	Marinelli *et al.* 2021
1 WWTP, United Kingdom (210.000 PE)	0.04 – 0.1 kgCH_4/kgCODinfluent	Aboobakar et al. (2013)
1 WWTP, China	0.08 % kg CH_4/kgCODin	Wang *et al.* 2011
2 WWTPs, China (Orbal oxidation ditch)	0.00285–0.00395 kg CH_4/kg CODremoved	Yan *et al.* 2013
(Reversed A^2O)	0.0007–0.0024 kg CH_4/kg CODremoved	Yan *et al.* 2013
(Anoxic/anaerobic/Oxic)	0.000.5–0.0012 kg CH_4/kg CODremoved	Yan *et al.* 2013
229 WWTPs, China	0.017–0.24 kgCH_4/kg COD	Zhao *et al.* 2019
Estimated value	0.0075 kg CH_4/kg (CODinfluent- CODsludge)	IPCC 2019
WWTPs	**CO_2 BIOGENIC EMISSION FACTOR**	**REFERENCES**
4 WWTPs, China (Anoxic/anaerobic/Oxic)	0.58 kg CO_2/kg COD	Bao *et al.* 2014
(Anoxic/oxic process)	0.68 kg CO_2/kg COD	Bao *et al.* 2014
(Oxidation ditch)	0.76 kg CO_2/kg COD	Bao *et al.* 2014
(Sequencing batch react.)	0.97 kg CO_2/kg COD	Bao *et al.* 2014
12 WWTPs, Italy (PE < 15.000)	1.1 kgCO_2/kgCODrem	Marinelli *et al.* 2021.
(PE > 15.000)	0.07 kgCO_2/kgCODrem	Marinelli *et al.* 2021.
1 WWTP, Italy (160.000 PE) (Aeration tank)	0.068 kgCO_2/kgCOD	Caniani *et al.* 2019.
(Secondary settler)	0.00017 kgCO_2/kgCOD	Caniani *et al.* 2019
2 WWTPs, China (Orbal oxidation ditch)	0.2613 kg CO_2/kg CODrem	Yan *et al.* 2014.
(Reversed A^2O)	0.2273 kg CO_2/kg CODrem	Yan *et al.* 2014.
(Anoxic/anaerobic/Oxic)	0.3193 kg CO_2/kg CODrem	Yan *et al.* 2014.

On the basis of the analysis performed in Table 3 and considering the influent average characteristics and the specific functioning data, in terms of typology and extension of the aeration basin and of the leakage in the biogas capture and storage systems in the WWTPs, the following conversion factor to estimate the GHGs direct emissions have been considered:

- N_2O: 0.035 kg N-N_2O per kg N removed
- CH_4: 0.035 kg CH_4 per kg COD removed
- CO_2 Biogenic: 0.73 kg CO_2 per kg COD removed
- CO_2 Fossil: 0.403 kgCO_2eq per kwh consumed (AQP, 2021)

It should be noted that 1 kg CH_4 is equivalent to approx. 30 kg CO_2 emitted, and that 1 kg N_2O is equivalent to approx. 300 kg CO_2 emitted (IPPC)

3 Results and discussion

The analysis of the data indicated that the WWTPs which involve aerobic digestion of sludge consume higher electric energy per m^3 of inlet wastewater, compared with those which involve anaerobic digestion (Ranieri *et al.*, 2021). In fact, the energy used by plants in terms of kWh/m^3 for all plants with aerobic digestion is on average 1.02 kWh/m^3 while for plants with anaerobic digestion it is significantly lower at 0.43 kWh/m^3 in average, in line with the literature, for similar climate conditions (Curtis *et al.*, 2010; Hernández-Sancho *et al.* 2011; Masłoń *et al.*, 2017;) reported electrical consumptions differences even higher. A further difference can be found between the average energy consumption for WWTPs with anaerobic digestion in Emilia Romagna and those in Apulia: in the former case the average consumption is lower, i.e. 0.33 kWh/m^3 compared to 0.53 kWh/m^3 of the Apulian plants. In any case, the results are in line, rather slightly lower than other Italian and international studies that report as a range of energy consumption of WWTPs, values between 0.4 and 0.7 kWh/m^3 (Campione & Campodonico 2017) and about 0.6 kWh/m^3 specifically in the Southern Italy (Utilitatis 2018;. Mizuta & Shimada 2010) report. For 17 Greek WWTPs operating at flowrates between 300 - 27,300 m^3/d (without anaerobic digestion facilities) the electric energy consumption has been reported at 0.903 ± 0.509 kWh/m^3 (Siatou *et al.*, 2020), while an analysis regarding 985 Japanese municipal WWTPs in different scale and system configuration reported that the specific power consumption (SPC) ranged from 0.44 to 2.07 kWh/m^3 for oxidation ditch plants and from 0.30 to 1.89 kWh/m^3 for conventional activated sludge plants without sludge incineration. (Mizuta and Shimada, 2010).

3.1 Energy consumption per incoming flow and per PE

The electric energy consumption, for all the WWTPs analysed, as a function of PE and flow are reported in the Figure 2. In most cases, the consumption of kWh/m^3 lies between 0.41 and 1.90 kWh/m^3 and between 14 to 100 kWh/PE*y. The above values are comparable with those referred for the Greek (Siatou *et al.*, 2020) and for the Japanese WWTPs (Mizuta and Shimada, 2010).

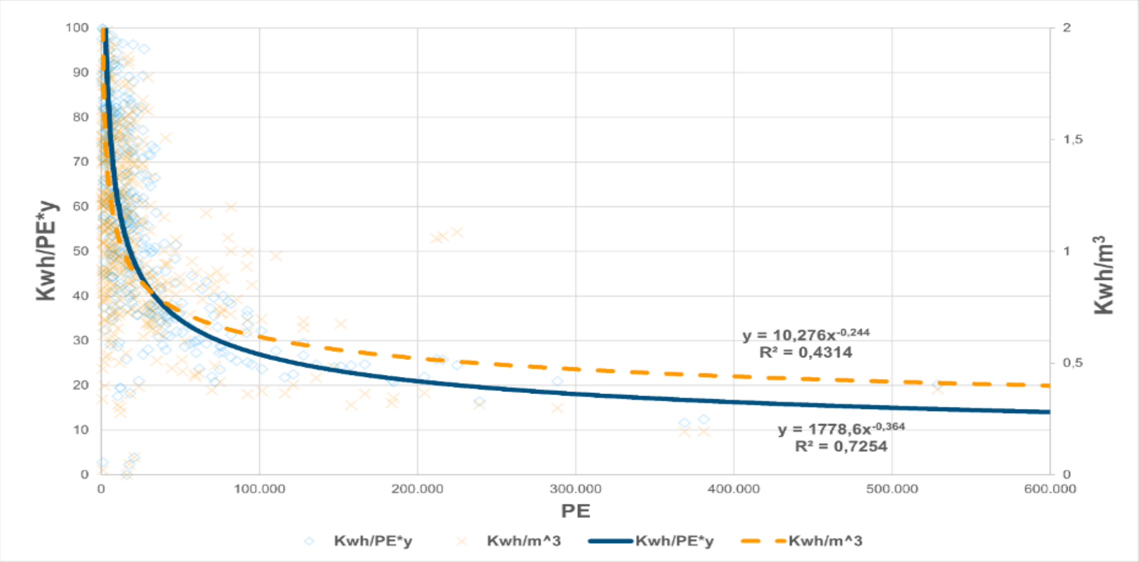


Figure 2 – Electric energy consumption for all Apulian WWTPs considered in terms of kwh/PE*Y and kwh/m^3 as a function of PE.

The electrical consumption as a function of PE per year are reported in the Figure 3 for WWTPs employing aerobic or anaerobic WWTPs. Figure 3 indicates that for WWTPs serving more than 33,000 PE, the adoption of anaerobic treatment is more favourable.

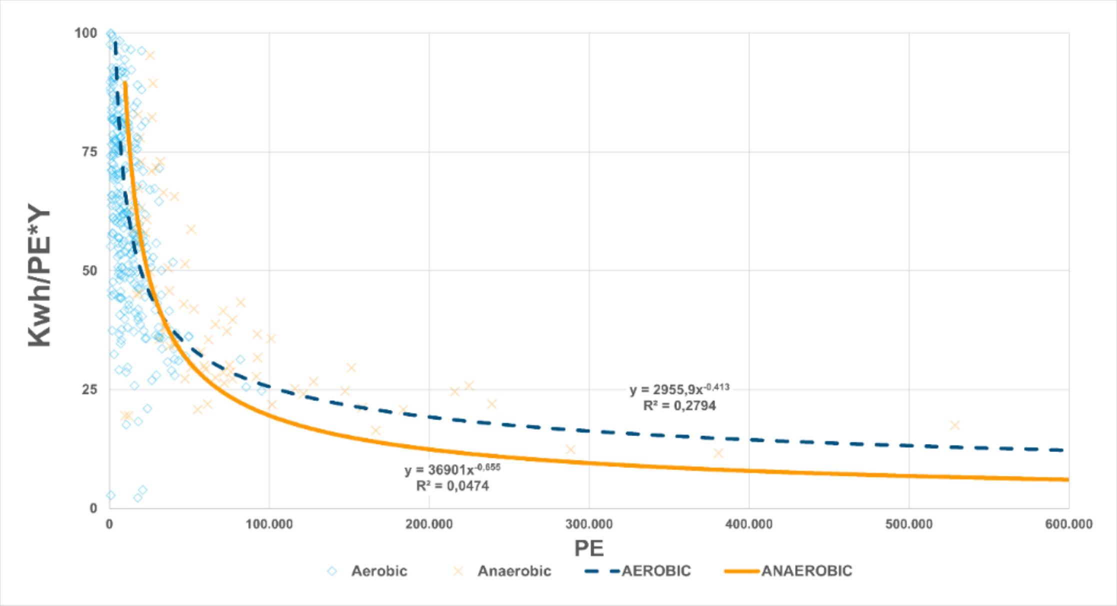


Figure 3 – Electric energy consumptions for Apulian WWTPs employing anaerobic or aerobic sludge treatment, in terms of kwh/PE*Y

<u>3.2 CO_2, N_2O and CH_4 Formation</u>

Biogenic CO_2 is emitted primarily in the aeration tank and in the aerobic sludge stabilization tank due to the organic substances' oxidation. CH_4 is mainly generated in the anaerobic digester as the final product of organic matter reduction.

N_2O gas is an intermediate of biological processes, such as heterotrophic denitrification and nitrification (Figure 4). Thus, N_2O is produced primarily during the nitrification and denitrification processes, employed to remove nitrogenous compounds from wastewater. N_2O production occurs mainly in the activated sludge units (about 90%), while the remaining (about 10%) comes from the grit and sludge storage tanks (Law *et al.,* 2012). Its formation is enhanced when the denitrification process is operated at low pH, at the presence of toxic compounds or at low dissolved oxygen (DO) concentrations (Kampschreur *et al*., 2009). Nitrifying bacteria are able to produce N_2O under aerobic or anoxic conditions. In anoxic conditions, both ammonia- and nitrite-oxidizing bacteria may produce N_2O, while only ammonia-oxidizing bacteria may produce it under aerobic conditions. In the latter case, the production of N_2O is stimulated at low DO concentrations, at the presence of nitrite (NO_2^-) or at relatively high concentrations of organic matter (Kampschreur *et al*., 2009). N_2O may also be produced from chemical reactions taking place at the presence of hydroxylamine and nitrite (Soler-Jofra *et al.,* 2016).

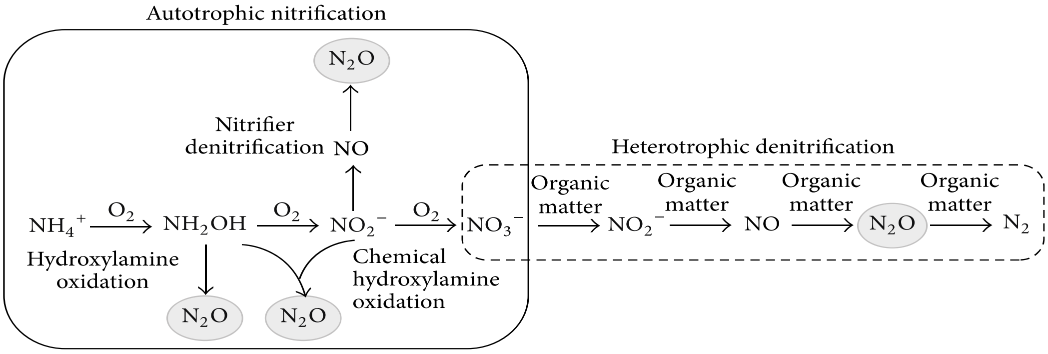


Figure 4 –Pathways of N_2O production during nitrification and denitrification (Campos et al., 2016).

3.3 Assessment of GHGs emissions.

The total GHGs production per Person Equivalent per year by the 183 Apulian WWTPs has been calculated based on the factors examined above (Figure 5) and has been found to about 103 $kgCO_2eq/(PE\cdot y)$ for aerobic WWTP and to about 134.6 $kgCO_2eq/(PE\cdot y)$ for anaerobic WWTP. The values are in good agreement with those reported by Parravicini *et al.* (2022).

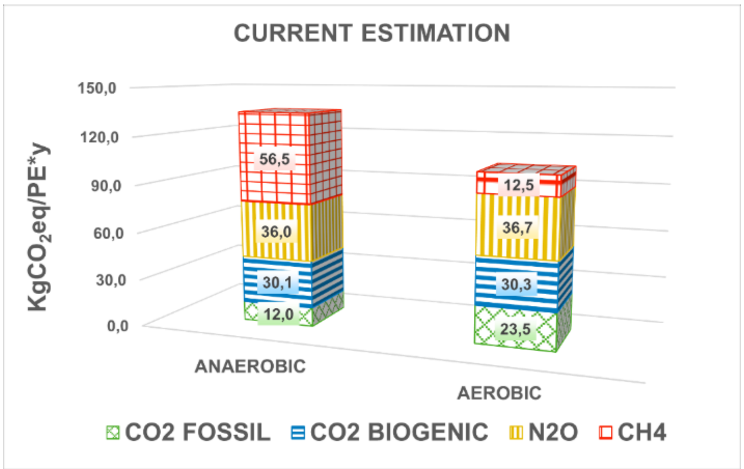


Figure 5 - Total $kgCO_2/(PE\cdot y)$ calculated for the 183 Apulian WWTPs employing aerobic or anaerobic sludge management.

CH_4 represents the highest contribution to the total CO_2 equivalent for WWTP with anaerobic sludge management, primarily due to CO_2 leakages in the biogas capture and storage systems. Compared with the WWTPs employing aerobic sludge management, the WWTPs with anaerobic sludge management emit higher quantities of GHGs on a per PE per year basis, as shown in Figure 6.

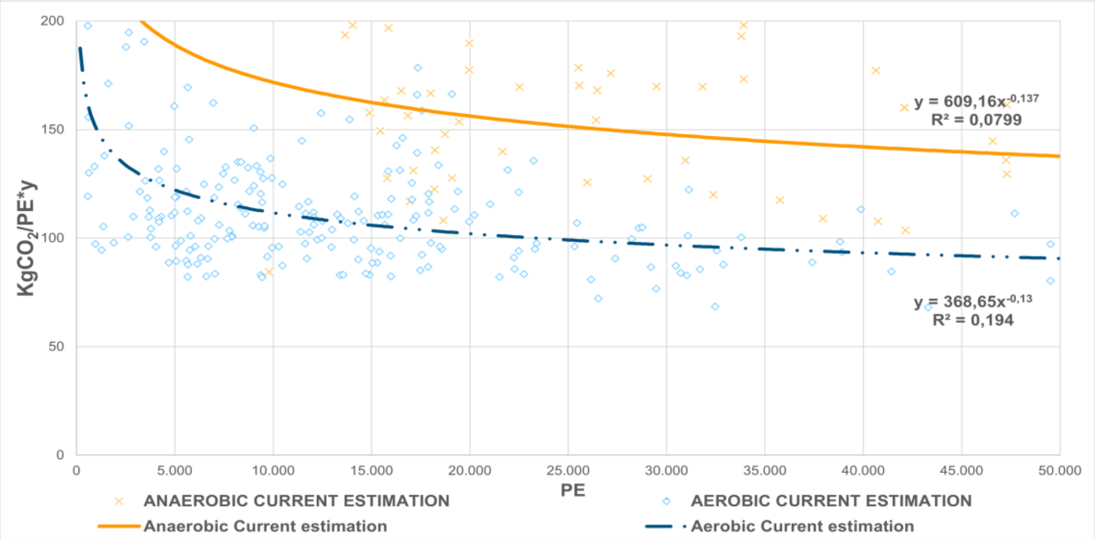


Figure 6 – Total GHGs emission for the 183 Apulian WWTPs employing anaerobic or aerobic sludge management systems, in terms of $kgCO_2eq/(PE \cdot y)$.

A series of operational and process measures have been outlined to control and decrease the total GHGs emitted in the Apulian WWTP, as described below.

3.4 Measures to reduce GHGs emissions.

GHG emissions may be drastically controlled by upgrading the performance of WWTPs. An analysis of the technical measures to be taken for upgrading the WWTPs aiming to GHGs reduction are disused below:

With respect to energy consumption, the introduction of monitoring system governed by Artificial Intelligence (AI) in the aeration tank and in the pumping, systems will drive to significant reduction of electric energy usage.

Artificial intelligence (AI) is applied in aeration systems that represents the most energy-consuming part of the wastewater treatment. AI is constituted by an intelligent control system that include an accurate real-time control of DO concentration, Oxidation-Reduction Potential and temperature that enable signal for intermittent and controlled aeration on the basis of the analysis of the functioning preceding wastewater characteristics data. The structure of the system consists of a feedforward controller based on a Radial Basis Function (RBF) network and an improved Proportion Integral Differential (PID) controller built on a Back-Propagation (BP) neural network. The proposed system reduced the total aeration time by 32 % meanwhile achieved higher efficiency of COD removal and a more efficient nitrification.

CO_2 biogenic: Reduction of biogenic CO_2 may be reached by converting aerobic sludge treatment systems into anaerobic ones and recovering biogas (mixture of CH_4 and CO_2) for energy production.

N_2O: Reduction of N_2O may be achieved by improving the performance of the WWTPs using AI, ensuring a complete anaerobic condition in nitrification-denitrification step resulting to the avoidance of intermediate biological steps, which are primarily responsible for the formation of N_2O.

CH_4: Reduction of CH_4 emissions may be reached by upgrading the existing anaerobic treatment systems, eliminating the leakages and increasing the production of CH_4 per kgCOD removed.

A preliminary study carried out on existing Apulian WWTP that have been upgraded has been evaluated by considering the output analyses and mass balance for each WWTP. With the implementation of upgrading measures, a consistent reduction of GHGs emitted is expected, which has been approximately calculated as 71% for CH_4, 57% for the N_2O, 20% for biogenic CO_2 and 15% for fossil derived CO_2.

As a result, for WWTPs with anaerobic sludge management, GHGs emissions are expected to be reduced from 134.6 $kgCO_2eq/(PE \cdot y)$ as reported in Figure 5 to 63.3 $kgCO_2eq/(PE \cdot y)$ as reported in Figure 5, while for the ones employing aerobic sludge management the reduction is expected from 103 $kgCO_2eq/(PE \cdot y)$ as reported in Figure 5 to 70 $kgCO_2eq/(PE \cdot y)$ as reported in Figure 7. Following the above changes, the highest GHGs contribution will be due to biogenic CO_2, for both types of WWTPs; while the fossil derived CO_2 emissions are expected as 18.8 and 9.6 $kgCO_2eq/(PE \cdot y)$, for aerobic and anaerobic based WWTPs, respectively. All the correlations analysed have been statistically significant.

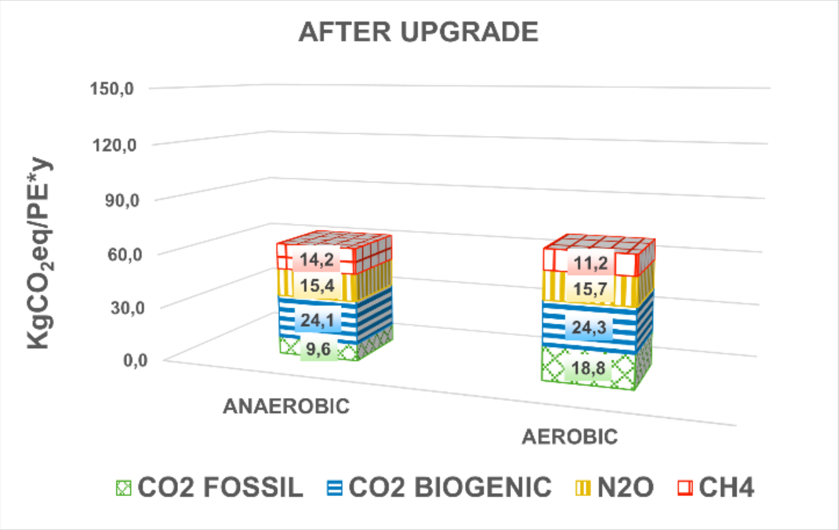


Figure 7 - Total $kgCO_2eq/(PE \cdot y)$ calculated for the 183 Apulian WWTPs employing aerobic or anaerobic sludge management, following upgrade.

Consequently, following the adoption of the described measures it is expected that anaerobic WWTPs would emit less GHGs on a PE per year basis. As shown in Fig. 8, anaerobic WWTPs with capacities above 30,000 PE are expected to produce less GHGs in terms of ***$kgCO_2eq/(PE \cdot y)$.***

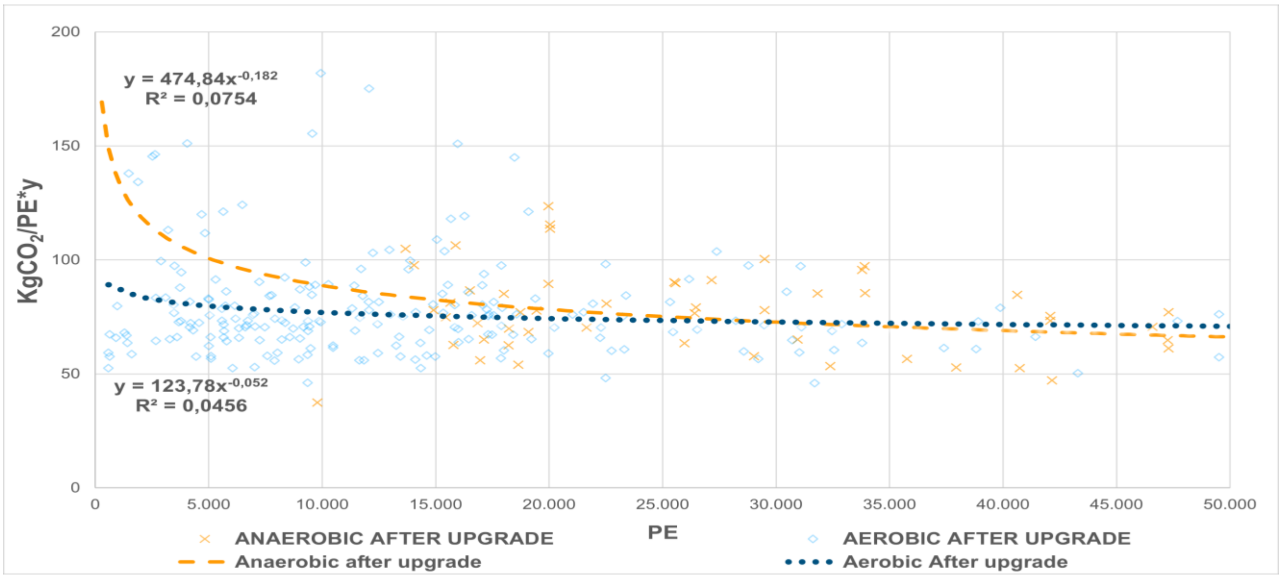


Figure 8–Total GHGs emission for the 183 Apulian WWTPs employing anaerobic or aerobic sludge management systems, in terms of $kgCO_2eq/(PE \cdot y)$, following upgrade.

4 Conclusions

An evaluation of the operative functioning data of 183 WWTPs in Apulia (Southeast of Italy) has been carried out 140 WWTPs are equipped with aerobic sludge digestion and 43 with anaerobic sludge digestion. It has been calculated that WWTPs with capacity greater than 33,000 PE consume less energy, on a PE per year basis, if they employ anaerobic sludge digestion systems.

On the basis of the factors examined for the studied WWTPs, the total GHGs emissions have been calculated as 103 and 134.6 kgCO_2 eq/(PE•y) for the ones employing aerobic or anaerobic sludge management systems, respectively.

It has been pointed out that lower CO_2eq emission per PE can be reached, particularly for anaerobic WWTPs, through the adoption of appropriate operational and process measures: ameliorating the CH_4 production and capture in the anaerobic step; upgrading the biological process with artificial intelligence based control (for improving the performance of the aerobic-anoxic phases in the nitrification-denitrification steps to reduce the production biogenic CO_2 and the N_2O formation).

With the implementation of upgrading measures, a consistent reduction of GHGs emitted is expected, which has been approximately calculated as 71% for CH_4, 57% for the N_2O, 20% for biogenic CO_2 and 15% for fossil derived CO_2.

Consent to Participate

Not applicable

Consent to Publish

Yes

Authors Contributions

The contribution of the authors is parithetic

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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